

DETECTORS FOR FUTURE CMB OBSERVATIONS

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ABSTRACT

The stunning progress in CMB observations in recent years has transformed cosmology. Yet, we have only begun to explore this most valuable relic of the early universe. The state of CMB observations and technology today is comparable to that of IR astronomy 25 years ago. We have had just a glimpse of what the CMB sky looks like, and that glimpse fully confirms theoretical expectations that the details of the structure and evolution of the Universe are encoded in the anisotropy of the CMB. The detector systems used to make these observations hark back to IRAS: limited hybrid focal planes composed of a small number of individual detectors. A compelling scientific case exists for CMB observations with far greater sensitivity and angular resolution than will be achieved by either MAP or Planck. This next step will require a revolution in detector systems that will be both challenging and expensive to accomplish. Motivated by the enormous scientific potential, a strong and vibrant community has made remarkable progress in demonstrating new and exciting detector concepts. However, a significant increase in funding for this community will be necessary in order to (i) mount the sub-orbital experiments necessary to prove that these detector *concepts* can be turned into useful detector *systems* and (ii) support the infrastructure necessary to turn these systems into flight-worthy hardware.

INTRODUCTION – A REVOLUTION IN COSMOLOGY

This is an extraordinary time. We have arguably understood more about the structure and evolution of our universe in the past 5 years that we have in all previous history. Observations of the Cosmic Microwave Background (CMB) have played a central role in igniting this age of discovery, and will remain at its core for decades to come.

The CMB provides us with a clear picture of what the Universe was like when the first atoms formed at redshift $\sim 10^3$, ($t/t_0 \sim 3 \cdot 10^{-5}$). The first experiments to resolve the characteristic scale of the extremely faint ($\Delta T_{\text{rms}} \sim 100 \mu\text{K}$) patterns of temperature anisotropy showed that the geometry of the Universe is flat; strong evidence in favor of Inflation. The most recent generation of experiments that have produced resolved images of these structures yield a remarkable consistent picture of a Universe that was born in an inflationary epoch, and is now composed of $\sim 2/3$ “dark energy”, which is causing the expansion to accelerate, and $\sim 1/3$ matter, the vast majority of which is in an unknown but presumably weakly interacting form. The protons, neutrons and electrons that we and the visible universe are made of constitute only $\sim 5\%$, of the mass-energy density of the universe. The stunning agreement between the value of the baryon density determined via the CMB and that obtained via BBNS and observations of the relative abundance of the light elements is confirmation that our fundamental understanding of the origins of the CMB, and of our interpretation of the faint patterns imprinted in it, is correct.

Most revolutions in astrophysics are driven by advances in instrumentation. What specifically has driven the recent leaps in CMB observations? Two quite different technologies have achieved comparable results: High Electron Mobility Transistors (HEMTs) and bolometric detectors. Because of the highly specialized and demanding nature of CMB instrumentation, it has been - and will increasingly be - essential to closely couple the development of each of these technologies to the development of real instruments and observing strategies. Even more than increases in individual detector sensitivity, the next generation of CMB instrumentation will require the development of more sophisticated detector *systems* - including coolers, cooled optics, signal modulation, and multiplexed readout electronics - in order to meet the stringent requirements both for sensitivity and control of systematic sources of error.

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WON'T MAP & PLANCK DO EVERYTHING?

In a word, no. Together, MAP and Planck will measure the power spectrum of the temperature anisotropy of the CMB to the fundamental “cosmic variance” limit over essentially the entire range of angular scales on which “primary” anisotropies – structures imprinted in the CMB at $z \sim 1000$, dominate. This will be a stunning achievement, but it will only begin to exploit the full potential of the CMB. In order to understand what remains to be done, it is useful to look in detail at the performance specifications of the High Frequency Instrument (HFI) on Planck. This instrument will achieve the highest angular resolution, the broadest frequency coverage, and the highest sensitivity to both temperature anisotropy and polarization of any currently planned CMB orbital mission, and thus serves as a useful point of departure for future work.

The HFI focal plane contains 48 individual bolometric detectors. The detectors are cooled to 0.1 K, and view the sky through a 0.1K feedhorn and filters, 1.6K filters, a 4K feedhorn and filters, and a ~ 60 K, off-axis telescope. The detectors are near background-limited, but the backgrounds are dominated by emission from the 4K and 60K optics, so further improvement in sensitivity is in principle possible with existing detector technology. There is, currently, $\sim 30\%$ margin between the current best estimates (CBEs) of sensitivity and the sensitivity goals for the mission; both are given in Table 1.

Table 1: Limits to the Sensitivity of the Planck HFI. ^(a)

Frequency	Angular Resolution	Goal Sensitivity ^(b)	CMB BLIP ^(c)	CMB+Instrument BLIP ^(d)	CBE Detector ^(e)	CBE Total ^(f)
[GHz]	[arcmin]	[$\mu\text{K}_{\text{CMB}} \text{sec}^{1/2}$]	[$\mu\text{K}_{\text{CMB}} \text{sec}^{1/2}$]	[$\mu\text{K}_{\text{CMB}} \text{sec}^{1/2}$]	[$\mu\text{K}_{\text{CMB}} \text{sec}^{1/2}$]	[$\mu\text{K}_{\text{CMB}} \text{sec}^{1/2}$]
100	9	50	16	24	29	38
143	7	60	16	26	32	41
217	5	90	18	39	47	61
353	5	275	28	128	154	200

- a) Mm-wave channels only. There are additional channels at 545 and 857 GHz.
- b) Goal for each detector chain sensitive to total intensity. There are 4 such detectors at each frequency. There are 8 more detectors at each of 143, 217 and 353 GHz sensitive to a single linear polarization, with $2^{1/2}$ x reduced sensitivity.
- c) Ultimate background limit due to the CMB, given the HFI bandwidth (30%) and optical efficiency (50%)
- d) Background limit due to the combination of CMB and emission from the Planck HFI optics.
- e) Current Best Estimate of bolometric detector noise, including amplifier noise.
- f) Current Best Estimate of the total noise due to the quadratic sum of background and detector noise.

THE FUTURE: CMB POLARIMETRY AND SZ ASTRONOMY

As part of the last decadal review process, NASA established a panel on the Future of CMB Observations¹. The panel concluded were that there were two exciting new types of CMB observations for which Planck would be only the beginning. These are (i) observations of the polarization of the CMB, which offer to the potential to study physical processes at energies as high as 10^{19} GeV, and (ii) arcmin-scale observations of the Sunyaev Zeldovich effect in clusters of galaxies, which will allow the study of the early phases of structure formation in the universe. In the 3 years since this report was written, the theoretical and observational cases for each have become increasingly compelling.^{2,3,4}

CMB Polarimetry: Seeing Beyond the Surface of Last Scattering

The CMB is polarized by several mechanisms. Thompson scattering at $z \sim 10^3$ will produce polarization with amplitude a few percent of the temperature anisotropy, in a distinctive pattern that has zero curl. The power spectrum of this polarization is, in principle, an even sharper probe of cosmological parameters than the temperature anisotropy. It has yet to be used simply because the signal has remained beyond our ability to detect it, but this will soon change

Two mechanisms can produce polarization non-zero curl. Gravitational lensing dominates on sub-degree scales. It is possible to reconstruct the global properties of the matter distribution from this signature⁴. Most exciting is the coupling of the CMB to the gravity wave background (GWB) that is a relic of inflation. The GWB will imprint a non-zero curl polarization in the CMB on degree scales with an amplitude that may be detectable. Polarimetry of the CMB thus offers a unique possibility of probing the epoch of inflation.

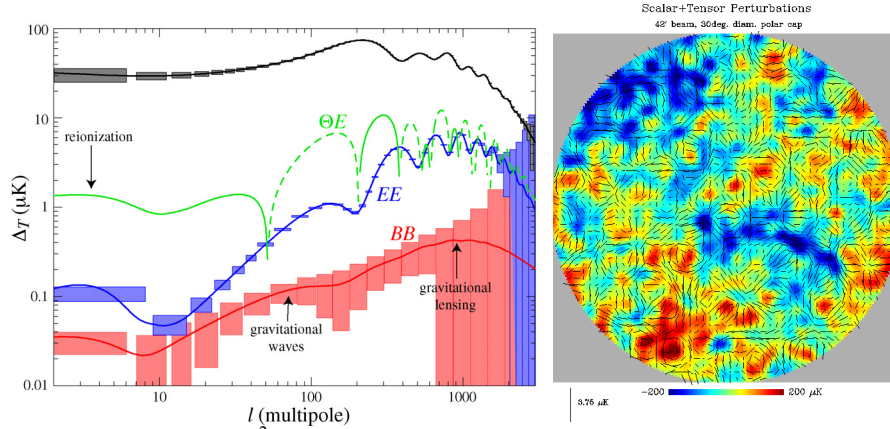


Fig 1. left (from Hu and Dodelson²) The power spectra of CMB temperature and polarization anisotropy. The compelling scientific targets include establishing the epoch of reionization, using gravitational lensing of the CMB to reconstruct the global distribution of matter and, most ambitious, detecting the gravity-wave background due to inflation. The errors shown represent the goal sensitivity of Planck, but do not include systematic errors. Right (Hivon⁴) A simulation of the polarization and temperature anisotropy fields.

Planck is not optimized to measure CMB polarization. Planck will have sensitivity to linear polarization at 30, 45, 70 and 100 GHz (LFI) and 143, 217 and 353 GHz (HFI) but, as Roger Hildebrand has wisely emphasized, “sensitivity to polarization does not a polarimeter make”. In particular, Planck has no mechanism for rapid modulation of the input polarization, and thus lacks an essential ingredient for suppressing systematic sources of error. Given the expected amplitude of the polarization signals ($< \sim 10^{-7}$ of intensity for GWB induced “B-mode” polarization), it is quite possible that Planck will not reach the sensitivity limits indicated in Fig 1, which include only statistical noise.

Sunyaev-Zeldovich Astronomy: Determining the Evolution of Large-Scale Structure

The Sunyaev-Zeldovich effect should be a uniquely powerful probe of the formation of large-scale structure. There are two SZ effects. The thermal effect has an amplitude proportional to the pressure of the plasma integrated along the line of sight through the cluster and has a unique spectral signature: the amplitude of the effect changes sign at 217 GHz. The kinetic effect is directly proportional to the peculiar velocity of the cluster and has a spectral signature identical to that of primary temperature anisotropies.

The potential of the SZ effects lies in the fact that the surface brightness of both effects is independent of redshift (due to the increase in T_{CMB} with redshift). Thus, if the angular resolution is sufficient to resolve clusters of a particular mass scale, *the detection rate becomes independent of redshift*. SZ observations with angular resolution $> \sim 1'$ can, in principle, provide an unbiased census of the co-moving density of clusters as a function of redshift, and thus trace the formation of large-scale structure. Such observations would provide an important constraint on the equation of state of the dark energy.

Planck will detect $> 10^4$ clusters via the SZ effect, but will be biased strongly towards brighter and closer clusters. Though Planck will be uniquely sensitive to extended SZ emission, significantly higher angular resolution (and thus a significantly larger aperture) will be required to begin for SZ astronomy.

FUTURE DETECTOR NEEDS

CMB Polarimetry

There remain no published detections of CMB polarization, little is known of the foregrounds that will confuse these measurements, and we have only just begun to grapple with the issues of instrumental systematics. What we do know is that the signal levels will be very small; we will need both extremely high sensitivity and significantly more powerful techniques for suppression/rejection of systematic effects than we have demonstrated to date. In addition, though there is no reason to believe that the foregrounds will prove significantly more troublesome for polarimetry at sub-degree scales, the ultimate goal of separating “B-mode” from “E-mode” polarization will require high fidelity maps with sub- μK sensitivity on super-degree scales. Foregrounds are likely to limit the ultimate precision of these observations, and thus experiments will ultimately require a very broad range of frequencies to enable the tiny imprint of the primordial gravity-wave background on the CMB to be convincingly isolated.

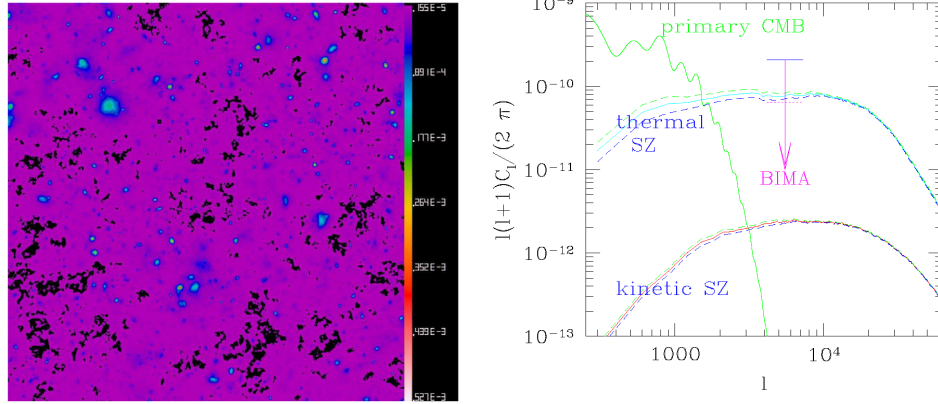


Fig 2. (adapted from Zhang, Pen and Wan⁶) left Simulation of the thermal SZ effect in an $\sim 1.2 \times 1.2$ degree field. Right The predicted contribution to the angular power spectrum of the thermal and kinetic SZ effects. The amplitudes are strongly dependent on σ_8 . The thermal effect can be distinguished from primary anisotropy, and from the kinetic effect, by its spectrum.

A generic case can be made that (i) the search for the CMB polarization signature of the gravity-wave background from inflation must ultimately be done from space and (ii) we will need at least one (and likely more) generations of sub-orbital experiments to teach us how to build the orbital mission.

Why do mm-wave polarimetry from space? Instruments with the capability of instantaneously differencing the two linear polarizations in a single beam should be able to reject virtually all atmospheric noise and thus operate perfectly well from high and dry sites where the total opacity is low. In fact, it is likely that we will soon have detections of CMB polarization on sub-degree scales from such experiments. There are two compelling reasons, however, for going to space. First, sensitivity will always be at a premium and there is a very significant advantage (an order of magnitude in sensitivity) to be had with the lower backgrounds available in space. Second, and most compelling, the ultimate goal of “seeing” inflation will require high fidelity maps over large angular scales with extremely well-understood noise properties. An orbital experiment that can rapidly compare widely separated parts of the sky will have fundamental advantages in suppressing systematic sources of error relative to a ground based experiment operating in 1 g and under an atmosphere that is $\sim 10^7$ brighter than the CMB even at the best sites.

Sub-Kelvin bolometers are expensive to implement. Thus HEMT amplifiers, which can achieve noise temperature well below their physical temperature, and are relatively insensitive to many sources of noise power that can contaminate the CMB signal, are an attractive choice.

Unfortunately, HEMT amplifiers currently lag significantly behind bolometers in sensitivity. Table 2 compares the sensitivity goals of one Planck focal plane element to some benchmark sensitivities that might be achieved in a next-generation CMB mission. The sensitivity quoted is the NET/feed. This is equal to the NEQ/feed if each feed contains two detectors, each sensitive to one linear polarization. The system NEQ for N feeds will be $(2/N)^{1/2}$ NET ($2^{1/2}$ times higher than the system NET) assuming that half of the feeds are used to measure each of Q and U. The possibility of extracting both Q and U from a single feed in the case of a coherent detection system (which is sensitive to both amplitude and phase) has already been assumed in the table, by giving the sensitivity of the future HEMT system as $2^{-1/2}$ NET.

The main points that are independent of detailed assumptions are: (i) existing Polarization Sensitive Bolometer (PSB) technology similar to that now being built for Planck HFI could achieve $\sim 35 (2/N)^{1/2} \mu\text{K}_{\text{CMB}} \text{sec}^{1/2}$ sensitivity to Q and U at 70 to 150 GHz, where galactic foregrounds are expected to be lowest. (The $\sim 2.5x$ improvement over Planck comes from assuming a reduced instrument background of 1K RJ.) (ii) if current research in HEMT amplifiers yields devices operating at $\sim 3x$ the quantum limit over $\sim 30\%$ bandwidths (compared to the $\sim 7x$ QL currently achieved at 100 GHz), and one assumes that both Q and U are extracted from each feed, then sensitivities of $50 (2/N)^{1/2} \mu\text{K}_{\text{CMB}} \text{sec}^{1/2}$ Q and U could be achieved at frequencies below ~ 100 GHz. (iii) if sensitive observations at frequencies above 100 GHz are necessary, as seems likely, then a bolometric detector system will have an overwhelming advantage in sensitivity. (iv) antenna-coupled bolometers, if implemented, can cover the entire frequency range of interest with sensitivity comparable to or higher than that of HEMT amplifiers, eliminating the need for a hybrid focal plane.

Table 2: Comparison of current, future and ultimate achievable sensitivity to CMB polarization

Frequency	PLANCK HFI NET/feed ^(a)	Bolometer NET/feed ^(b)	3xQL HEMT 2 ^{-1/2} NET/feed ^(c)	CMB BLIP NET/feed ^(d)
[GHz]	[$\mu\text{K}_{\text{CMB}} \text{sec}^{1/2}$]	[$\mu\text{K}_{\text{CMB}} \text{sec}^{1/2}$]	[$\mu\text{K}_{\text{CMB}} \text{sec}^{1/2}$]	[$\mu\text{K}_{\text{CMB}} \text{sec}^{1/2}$]
30	120 (LFI)	45	40	19
45	140 (LFI)	38	42	18
70	180 (LFI)	33	48	17
100	220 (LFI)	31	59	16
150	60 (HFI)	33	91	16
220	90 (HFI)	48	185	18
350	275 (HFI)	160	882	28

- a) Goal sensitivity of each feed to $\Delta T = (\Delta T_x + \Delta T_y)/2$ and Stokes parameter Q or U, defined as $(\Delta T_x - \Delta T_y)/2$.
b) Sensitivity for 100 mK, Ge thermistor, Polarization-Sensitive Bolometer pair, assuming 1.0K RJ instrument background, 50% optical efficiency and 30% bandwidth.
c) Same for HEMT amplifier with noise 3x quantum limit over 30% bandwidth. The sensitivity quoted is $2^{-1/2} \times \text{NET}$, to take into account the ability to measure Q and U simultaneously with appropriate post-amplification electronics.
d) The ultimate limit to sensitivity to Q or U, for zero instrument background and a noiseless direct detector.

A bolometric polarimeter requires a method of cleanly modulating the input polarization prior to detection. Cooled rotating waveplates would be extremely expensive and risky to implement. An alternative it so use Faraday rotation in cylindrical waveguide. A prototype 100 GHz polarization modulator based on this principle has been developed by our group, in collaboration with Todd Gaier and Mike Seiffert at JPL, and appears quite promising. This “solid-state waveplate” allows the input polarization to be rapidly rotated prior to detection by a pair of polarization sensitive bolometers that are embedded in the waveguide. This scheme will first be tested in ~ 2004 by BICEP, a 100 and 150 GHz polarimeter designed to be sited at the South Pole, which will have approximately the same instantaneous sensitivity to CMB polarization as Planck.

In addition to being optimized for polarimetry, a next-generation CMB polarization mission will require significantly higher sensitivity as well, as there is no guarantee that the amplitude of the gravity-wave signal will be as large as that shown in Fig.1. The “Ge bolometer” sensitivities in Table 2 are ~ 2.5 x better than the goal sensitivity of the Planck HFI. The “CMB BLIP” column shows that only another factor of ~ 2 can be had by reducing instrument emission and detector noise to zero. More gains could be made by frequency multiplexing so that two or more of the requisite bands can share the same focal plane area. Finally, large filled arrays could, in principle, provide increases of a factor of ~ 1.5 in sensitivity over the $\sim 2F\lambda$ feedhorn arrays employed on Planck.⁷

SZ Astronomy

In comparison with the current state of CMB polarimetry, SZ astronomy is in a relatively mature state. The unmistakable signature of the effect has been detected by a variety of experiments. The challenge now is to develop instrumentation that will achieve mapping speeds sufficient to make routine the “serendipitous” detection in blank field surveys of high redshift clusters.

Much excitement has recently centered around the potential of a new generation of receivers built around large, arrays of bolometric detectors and coupled to large ground-based telescopes. To realize the full potential of this class of instruments will require an enormous leap in detector technology. Consider, for example, The Large Millimeter-wave Telescope, a 50 m dish that is scheduled to see first light in ~ 2004 . The telescope should ultimately achieve diffraction limited resolution at 217 GHz (the null of the SZ thermal effect, and of particular interest to exploiting the kinetic SZ effect) of ~ 0.15 arcmin. Filling even a modest 4' diameter field of view with $0.5F\lambda$ pixels will require well in excess of 1,000 pixels. Several groups at this workshop will report on exciting new detector architectures that will allow such large arrays to be realized. There are several options for (i) how to couple the radiation in each pixel (dense arrays of “pop-up” detectors or dense planar arrays of antennae or absorbers), (ii) how to detect the radiation (Transition Edge Superconducting (TES) detectors or Kinetic Inductance Detectors (KIDs), and (iii) how to multiplex the signals (time domain or frequency domain SQUID-based muxes for TES detectors, frequency-domain HEMT based muxes for KIDs).

The possibility of kilapixel arrays of background-limited detectors with sub-arcmin resolution operating near the peak brightness of the CMB is enough to make observational cosmologists giddy. We

should keep in mind, however, that we do not share the happy world of the optical astronomers, in which backgrounds are zero, detectors are noiseless, and all of the throughput of each pixel that does not couple to the sky is intercepted by perfectly dark surfaces. In the mm-wave world, straylight can very quickly degrade sensitivity, and filled arrays of bolometers, lacking feedhorns, are vulnerable to straylight. It will be essential to carefully control the optical environment of the bolometer array in order to achieve the full potential of the mapping speed. For a 100 GHz ground-based receiver, for example, the potential ~ 3 -fold advantage in mapping speed of a filled array of $1\text{ F}\lambda$ pixels over that of an array of $2\text{ F}\lambda$ feedhorns completely disappears (and rapidly turns into a disadvantage!) if the beam is intercepted by a Lyot stop at $T > 2\text{K}$. The requirements for space are even more stringent; the detector array must be completely shielded by surfaces $< \sim 1\text{K}$ ⁷. These constraints will be non-trivial to satisfy, emphasizing the need to develop useful *systems*, as opposed to detectors.

CONCLUSIONS

The future of CMB observations looks exceedingly bright – our community is very lucky to be participating in an unprecedented revolution of our understanding of the origins, structure and evolution of the universe.

The progress in CMB detection systems has been rapid and is now accelerating as a larger community becomes involved. This larger community of scientists attempting to build vastly more sophisticated instrumentation will require significant increases in funding if it is to remain vibrant.

A post-Planck orbital mission will be required to unambiguously detect the inflationary gravity-wave background via its imprint on the polarization of the CMB on angular scales of several degrees, and to make full use of the gravitational lensing signal imprinted on sub-degree scales. Exquisite sensitivity and exquisite control of systematic errors are both required. We have arguably more work to do on control of systematics than on increased sensitivity.

Detector systems for polarization must be optimized as systems, not as separately engineered detectors, polarization analyzers and polarization modulators. Developing and demonstrating a workable combination of technologies that can be flight-qualified will require strong support for the sub-orbital experiments that will provide the proving ground.

Enormous progress in SZ astronomy can be expected from the advent of large bolometric mm-wave arrays on large (~ 5 to 50 m) ground based telescopes. Here, the signals to be detected are orders of magnitude higher than the polarization signal, and it is largely mapping speed (in several bands covering the range of 100 to 300 GHz) that is at a premium. Arrays with large numbers of multiplexed detectors are one way to achieve high mapping speed. Filled arrays (without feedhorn coupling optics) are vulnerable to straylight that can quickly erase the theoretical gains in mapping speed. Thus, it is again important to develop a detector system, including cryogenics and optics, rather than a detector.

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